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Analysis of Flow Over Weir and Under Ellipse Gate

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Abstract
Combined hydraulic structures are widely used in irrigation system for civil engineering water system works. The use of gate have regular shape is commonly used in hydraulic structures because it is easy to construction as compare with non-regular shape. The aim of this study is to investigate the effect of use gate have non-regular shape especially half ellipse shape with three different shape of weir such as rectangular, triangular and parabolic weir. This study concentrates on the effect of cross sectional area of flow that passes through ellipse gate on hydraulic parameter like flow rate, discharge coefficient, downstream water depth, and water surface profile shape and level. The present study addressed the aspect of geometrical dimension effect on hydraulic parameters. Also this study mention to the effect of Reynolds number on hydraulic variables such as flow rate and cross sectional area of flow that passes the gate. The present study concluded that it is better to use non-regular shape of gate in combined hydraulic structure with any shape of weir. Also, it is observed that it is favored to use non-regular shape for both gate and weir in construction of combined hydraulic structure due to their significant effect on discharge quantity and depth of water in downstream of flume or open channel in field taking in consideration that the water surface profile is always nonlinear.
Keywords: Hydraulic structure, half ellipse gate, parabolic weir, rectangular weir, triangular weir. Free flow condition.

1. Introduction

Gates and weirs were used extensively for flow discharge measurement and control in irrigation open channel flow. Problems concerning depositions and sedimentation are minimized by combined gates and weirs as outlined by Alhamid et al. (1997). There are only a number of works that deal with the combined underflow and overflow as discharge measurement devices available, e.g., Chow (1959), Ahmed (1985), and Naudascher (1991). Negm et al. (1994), for example, discusses the different characteristics regarding the combined flow over rectangular contracted weirs and below inverted triangular gates. El-Saiad et al (1995), however, investigates the effects of a triangular opening's notch angle in the cases where it is used both above and below the rectangular opening. It was discovered that a triangular above a rectangular opening is more efficient than the reverse. Alhamid et al. (1996), was presented a regression equation to predict the discharge over rectangular weirs and below triangular weirs. Negm (1995) also analyzed the many characteristics of the combined flow over contracted weirs and below contracted gates of rectangular shape that have unequal contractions. Another discharge prediction for combined flow over suppressed rectangular weirs and below gates was also presented by Negm (1996). In recent times, Negm et al. (1997) discussed the different effects caused by hydraulic and geometrical parameters on the combined discharge and presented discharge equations for triangular weirs above rectangular contracted gates and contracted rectangular weirs above triangular gates. It was proven that the prediction of the combined discharge through the usage of common discharge coefficients manages to produce significant errors. Combined-submerged flows over weirs and below gates were also analyzed and discussed by Negm et al. (1999), Alhamid (1999), Negm (2000), Negm et al. (2000a). It is observed that most of the previous studies considered only regular shape of weir and gates. Qasim et al. (2018) investigate the overlapping between weir and gate having a parabolic shape. It is found that the weir and gate cross sectional area of flow have significant effect on coefficient of discharge of combined hydraulic structure. Also, this study proves that the parabolic shape more efficiency as compare with regular shape.

The characteristics of the combined flow over weirs and below ellipse gates are investigated in this paper. Three different geometrical weirs such as rectangular, triangular and parabolic were used. Effects of hydraulic and geometrical parameters are discussed. Also, effects of Reynolds number are addressed.

2. Fluid Mechanics Consideration

The present study concern with three different shape of combined hydraulic structure or device (weir-gate) these are

2.1 Triangular weir (V-notch) – Ellipse gate

To find the flow-rate through composite device for the free flow situation, the flow-rate represents the incorporation of both weir and gate

$$Q_{theor} = Q_w + Q_g \qquad (1)$$

To obtain the flow – rate through weir (V-notch) (Streeter, 1989)

$$Q_{weir} = \frac{8}{15}\sqrt{2g}\ \tan\frac{\emptyset}{2}\ \ h^{5/2} \qquad (2)$$

To calculate the flow-rate through gate, from continuity equation (Streeter, 1989)

$$Q = V\ A \qquad (3)$$

$$Q_{gate} = V\ A = \sqrt{2gH}\ A \qquad (4)$$

For free flow

$$H = d + y + h \qquad (5)$$

$$Q_{act} = c_d\ Q_{theor} \qquad (6)$$

$$Q_{act} = c_d\left[\frac{8}{15}\sqrt{2g}\ \tan\frac{\emptyset}{2}\ \ h^{5/2} + \sqrt{2gH}\ A\right] \qquad (7)$$

2.2 Rectangular weir – Ellipse gates

To find the flow-rate through composite device for the free flow situation, the flow-rate represents the incorporation of both weir and gate

$$Q_{theor} = Q_w + Q_g \qquad (8)$$

To calculate the flow – rate through weir (Streeter, 1983)

$$Q_{weir} = \frac{2}{3}\sqrt{2g}\ b\,h^{3/2} \qquad (9)$$

To calculate the flow-rate through gate, from continuity equation (Streeter, 1989)

$$Q = V\ A \qquad (10)$$

$$Q_{gate} = V\ A = \sqrt{2gH}\ A \qquad (11)$$

For free flow

$$H = d + y + h \qquad (12)$$

$$Q_{act} = c_d\ Q_{theor} \qquad (13)$$

$$Q_{act} = c_d\left[\frac{2}{3}\sqrt{2g}\ b\,h^{3/2} + \sqrt{2gH}\ A\right] \qquad (14)$$

2.3 Parabolic weir – Ellipse gates

To find the flow-rate through composite device for the free flow situation, the flow-rate represents the incorporation of both weir and gate

$$Q_{theo} = Q_W + Q_g \qquad (15)$$

To calculate the theoretical discharge through weir (Bos, 1989)

$$Q_w = \frac{\pi}{2}\ \sqrt{f\,g}h^2 \qquad (16)$$

To calculate the discharge through gate (Streeter, 1983)

$$Q_g = V\ A = \sqrt{2\,g\,H}\ \ A \qquad (17)$$

For free flow

$$H = d + y + h \qquad (18)$$

$$Q_{act} = c_d\ Q_{theo} \qquad (19)$$

$$Q_{act} = c_d\ \left[\frac{\pi}{2}\ \sqrt{f\,g}h^2 + \sqrt{2\,g\,H}\ \ A\ \right] \qquad (20)$$

H: Upstream water depth of the gate
h: Water head above sharp crest weir
y: Vertical distance between weir and gate
d: Gate opening water depth
A: Cross sectional area of flow
b: Rectangular weir width
V: Velocity of flow through gate
f: Focal distance
g: Gravity acceleration
Q_{theor}: Theoretical discharge
Q_{act} : Actual discharge
C_d : Coefficient of discharge

3. Experimental Procedure

The experiments were carried out in a rectangular glass sided flume with a dimension of 200cm length, 15cm depth and 7.5cm width. The discharge is measured using the volume method while the water depth is measured by using point gage device. Figure 1 shows the combinations shapes which considered in the present work. Table 1 reviews selected dimensions of the triangular, rectangular, and parabolic models that fabricate from wood material. Table 2 reviews selected information that was obtained from experimental study performed in

laboratory. The following procedures are adopted in laboratory test (Qasim et. al., 2018).
1- The slope of the flume is always in horizontal position.
2- The models were fixed into flume at distance 80cm from the beginning of the flume.
3- The free flow condition is satisfied by removing the tail gate from the channel.
The above procedure was repeated for all models.

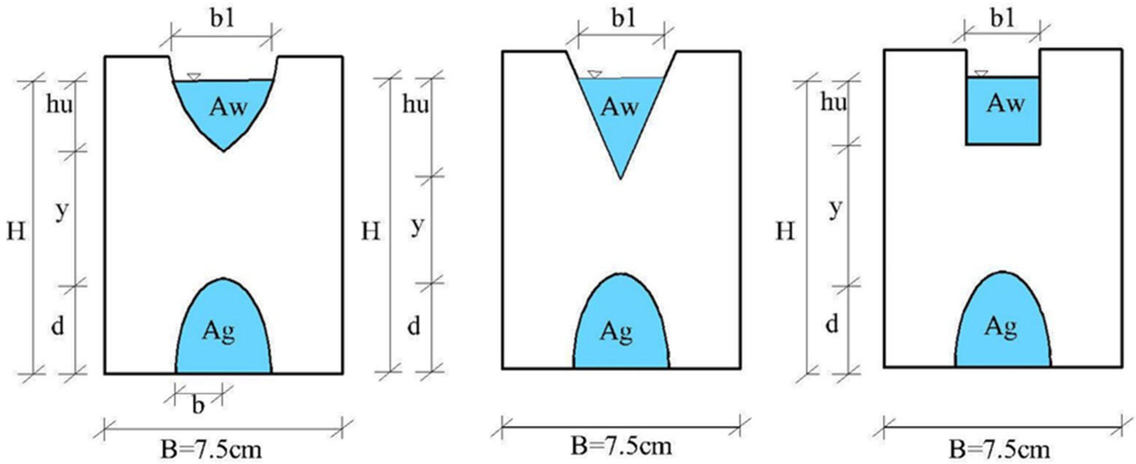

Figure (1) Definition Sketch for the Three Models of Combined Free Flow over Weir and under Ellipse Gate

Table 1. The Tested Model Dimensions and Details of Selected Different Shapes of weir and Ellipse Gate

Model	Model No.	h_u (cm)	y (cm)	d (cm)	b (cm)	b1 (cm)	H (cm)
Triangular Combined Weir with Ellipse Gate	1--5—3	3	3	3	1.5	2.59	9
Rectangular combined weir with Ellipse gate	2--3—2	2	4	3	1.5	2.31	9
Parabolic combined weir with Ellipse gate	3--4—1	1	4.5	2.5	1.25	3.464	8

Table 2. Table 2 Results of the Selected Experimental Models

Model No.	y/H	Ag/BH	Aw/BH	V (m/sec.)	$Q_{act.}$ (l/sec.)	Q_{theo} (l/sec.)	Cd	R_N
1--5—3	0.333	0.1047	0.0577	1.328	0.812	2.374	0.342	10830
2--3—2	0.444	0.1047	0.0684	1.328	0.801	1.132	0.708	10686
3--4—1	0.562	0.0818	0.0223	1.253	0.563	0.640	0.881	7509

Nineteen models were tested (7 of triangle shape, 6 rectangle shape, and 6 ellipse shape of weir and ellipse gate) involving the following limitations: $3\leq y \leq 4.5$, $2.5\leq d \leq 3$, $1.25\leq b \leq 1.5$, $0.866 \leq b1 \leq 3.464$, $1\leq h_u \leq 3$. Models are made of wood sheet 5mm thick beveled along all the edges at 45^0 with sharp edges of thickness 1mm (Qasim et. al., 2018). Models are fixed to flume using plexiglass supports. The selection of the flume and model material was based on the available laboratory facilities. In each test, combined flow rate, $Q_{act.}$, head over the weir, h_u, downstream flow depth, h_d, and upstream flow depth, H, are measured under free flow conditions. The triangular, rectangular, and parabolic weirs superposed with ellipse shape gate were adopted in the present study.

4. Result and Discussion

Study the hydraulic behavior of composite hydraulic structure represents a good idea due to interaction between over flow-rate and under flow-rate also due to interaction between geometrical dimension and hydraulic properties. So, the necessary and important subject in this work can be describing by studying the effect on non-regular gate shape on regular and non-regular weir. Three different shapes of weir are considered in this study these are rectangular, triangular, and parabolic weir respectively while the gate shape is half ellipse during all cases of study.

Based on continuity equation which represents direct proportional between the discharge and the cross sectional area of flow that passes through composite hydraulic structure, as the cross sectional area of flow increases the discharge that cross the hydraulic combined structure must increase. It is clear from figure (2) for rectangular weir the discharge increase with increase in the ratio *Ag/BH* for the range from 0.072 to 0.11, for parabolic weir the discharge decrease when the ratio *Ag/BH* between 0.072 to 0.095 and increase from the ratio range between 0.095 to 0.12. For triangular weir the discharge increase for the ratio range between 0.072 to 0.09 and then increase for the ration range between 0.09 to 0.11. For the rectangular, parabolic, triangular weir respectively the discharge that cross the composite device after the ratio equal to 0.11 will decrease. The clarification of this problem due to interaction between over flow velocity and under flow velocity, also due to effect of water head above weir which dominate on the quantity of flow rate that cross weir.

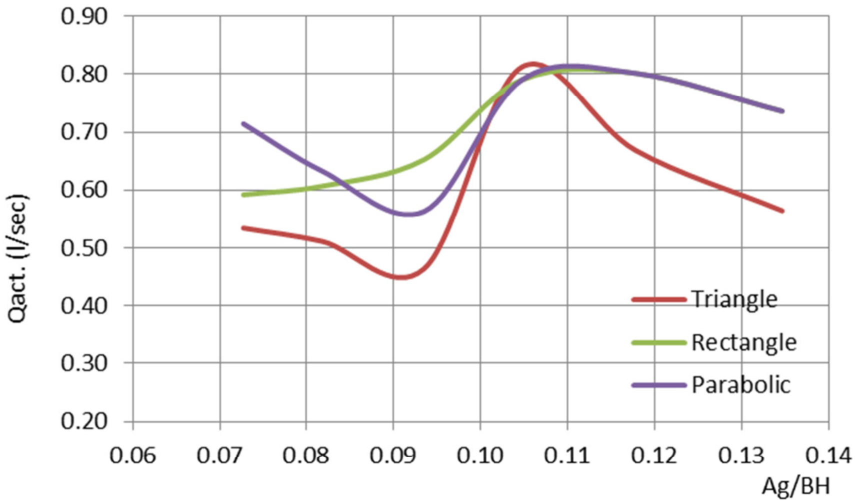

Figure (2) Variation of Actual Discharge with Area of gate

Figure (3) review the relationship between the discharge coefficient and the ratio *Ag/BH*. The discharge coefficient is inversely proportional with cross sectional area of flow that passes the device. So it is clear from figure as the ratio increase from 0.072 to 0.092 the coefficient of discharge increase after the ratio value equal to 0.092 the coefficient of discharge will decrease. Figure (4) shows the relationship between Reynolds number and the ratio *Ag/BH*. The flow velocity and water combined head has major effect on Reynolds number while the cross sectional area of flow that cross the gate has inversely relationship with flow velocity of water that passes from the gate take inconsideration these velocity depend on combined head of water. So the variations in relationship appear clearly in figure (4). Also the overlapping between over flow velocity and under flow velocity will reflect on the relationship between Reynolds number and the ratio *Ag/BH*. In all figures (2, 3 and 4) the value of the area of the gate is non-dimensionalzed by division of the hydraulic cross sectional area (B.H).

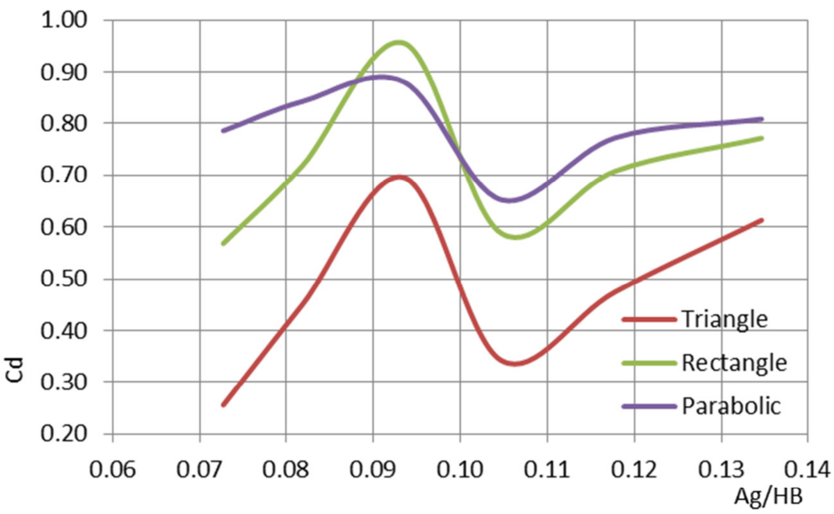

Figure (3) Variation of Coefficient of Discharg with Area of Gate

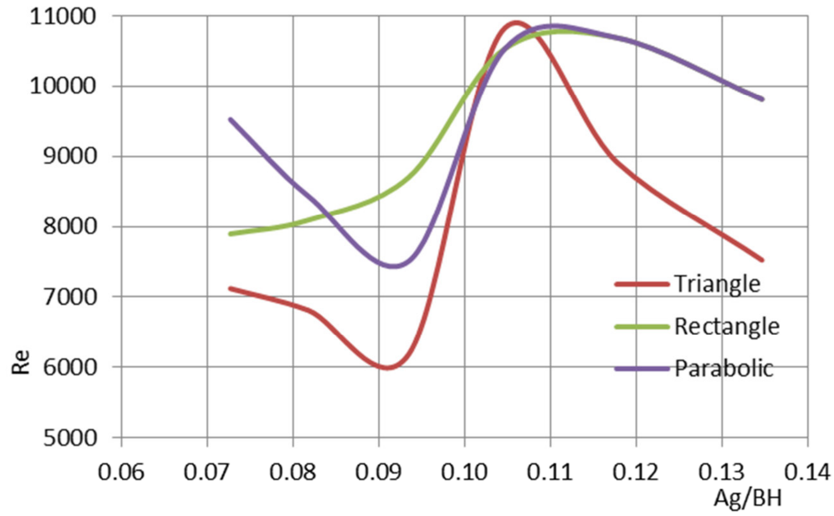

Figure (4) Variation of Reynolds Number with Area of Gate

Figure (5) review the relationship between the discharge and the ratio (y/H) it is obvious from figure as the ratio (y/H) increase the discharge decrease. This occurs due to increase in distance between weir and gate (y) and this lead to increase in more quantity of discharge intercepted or restricted behind the composite hydraulic structure. Figure (6) shows that discharge coefficient is directly proportional with the ratio (y/H). Theoretically, the coefficient of discharge has inverse relationship with the discharge that crosses the combined device. Depending on figure (5) which shows inverse relationship between flow rate and the ratio (y/H) that is supported by inverse proportional between flow rate and discharge coefficient, therefore, it is possible to conclude direct proportional between discharge coefficient and the ratio (y/H). It is evident from figure (6) that the non-regular shape weir which is represented by parabolic weir have higher coefficient of discharge compared with regular shape like rectangular and triangular weirs respectively.

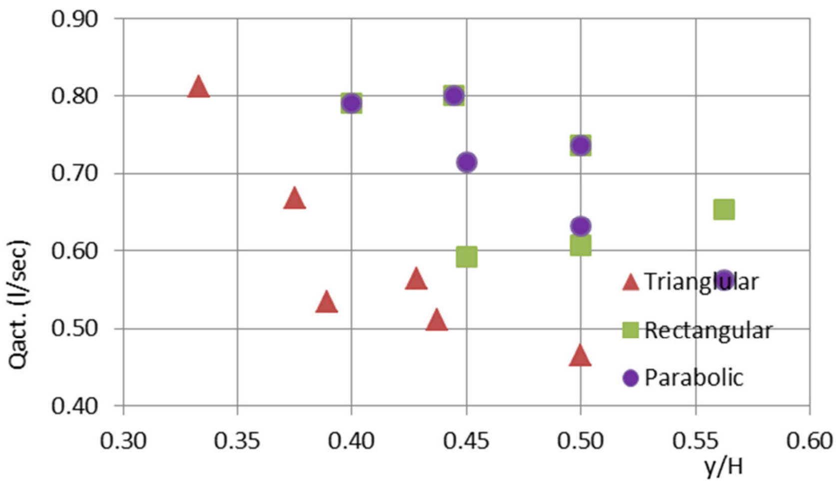

Figure (5) Variation of Actual Discharge with Depth between weir and Gate

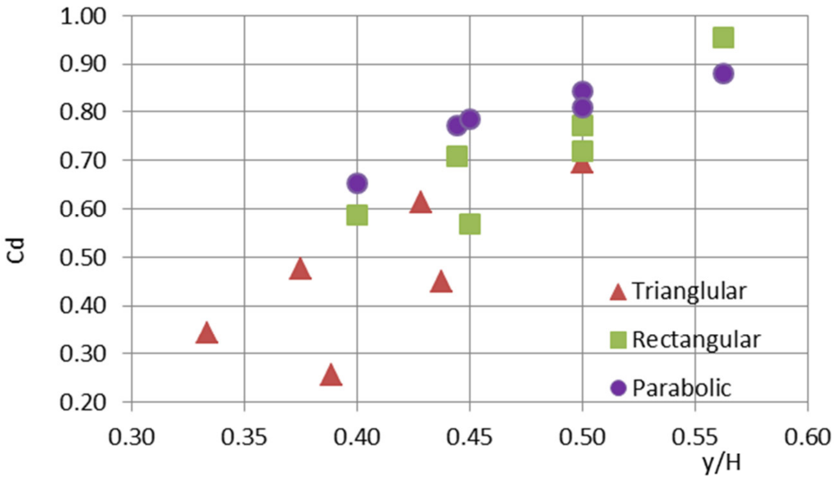

Figure (6) Variation of Actual Discharge with Depth between weir and Gate

It is evident from figure (7) direct relationship between the flow rate that cross the combined hydraulic structure and Reynolds number because both of them based on flow velocity and combined head so the increase in flow rate lead to increase in Reynolds number. It is obvious from figure (8) randomly relationship between discharge coefficient and Reynolds number due to interaction between over flow velocity and under flow velocity and combined head of water which more effective by the water head above weir.

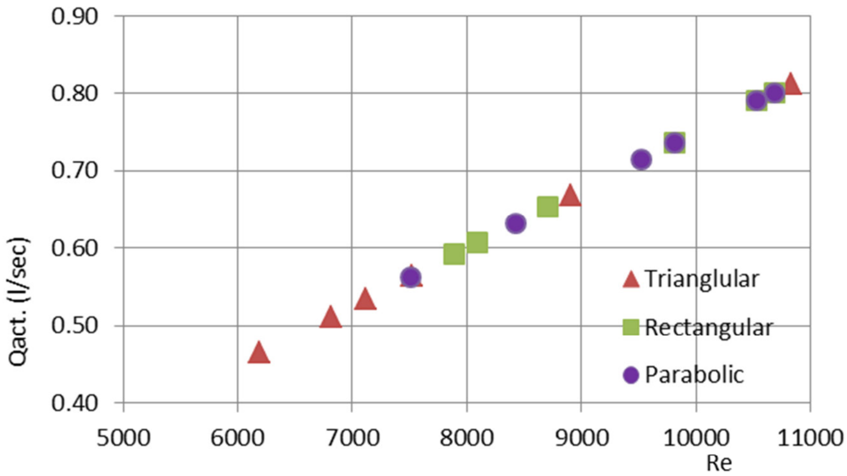

Figure (7) Variation of Actual Discharge with Reynolds Number

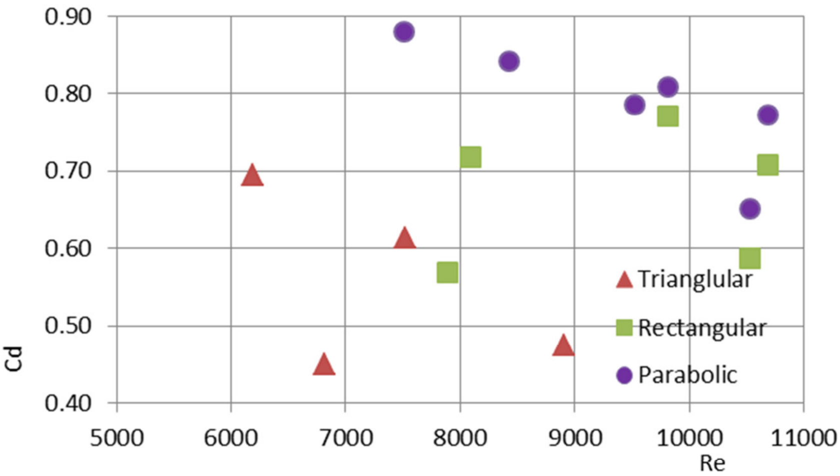

Figure (8) Variation of Discharge Coefficient with Reynolds Number

Figures (9 and 10) show the water profile in downstream of composite hydraulic structure. Figure (9) shows the relationship between downstream head and horizontal distance of flume in downstream to draw the water profile that result from triangular weir and half ellipse gate it is obvious that the water surface profile is nonlinear. While Figure (10) shows the relationship between downstream head and horizontal distance of flume in downstream to draw the water profile that result from parabolic weir and half ellipse gate it is obvious that the water surface profile is nonlinear. In both figures it is clear that the depth of water in case of non-regular shape which represented by parabolic weir and half ellipse gate lead to high water level in downstream as compare with other this happened due to large quantity of water cross the composite hydraulic structure in this condition. Figure (11) shows the relationship between water depths at downstream with horizontal distance of flume in downstream. It is clear that the non-regular shape produce high water level in downstream as compare with regular shape.

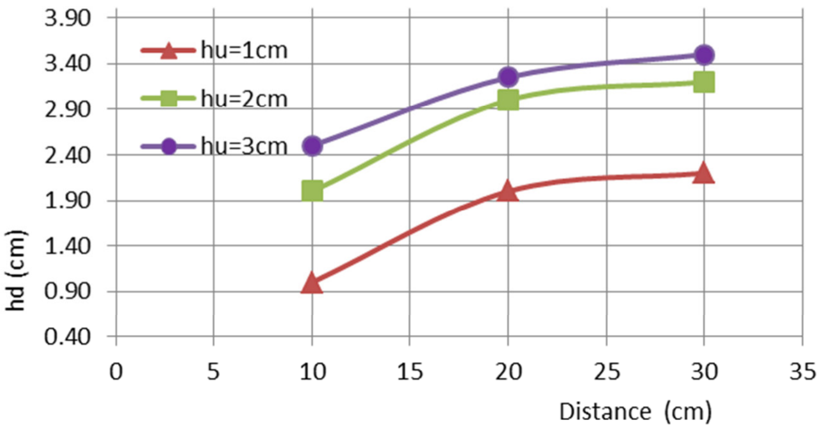

Figure (9) Variation of Downstream Water Profile with Head above TriangularWeir ($Ag=4.9cm^2$, d=2.5cm, y=3.5cm)

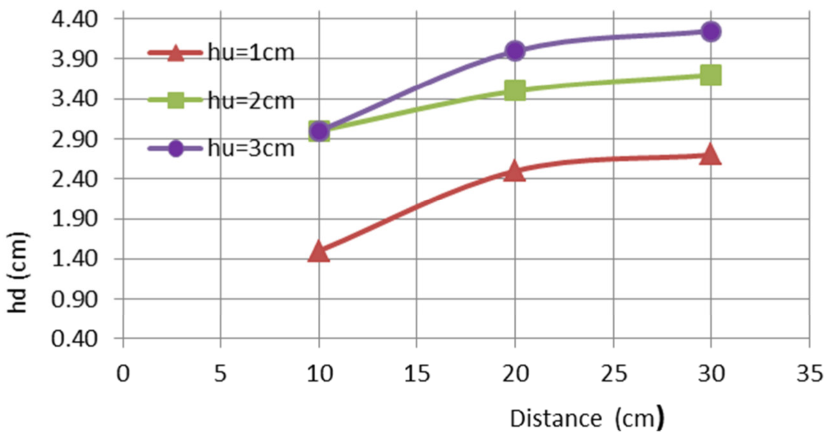

Figure (10) Variation of Downstream Water Profile with Head above Parabolic Weir (Ag=4.9cm^2, d=2.5cm, y=4.5cm)

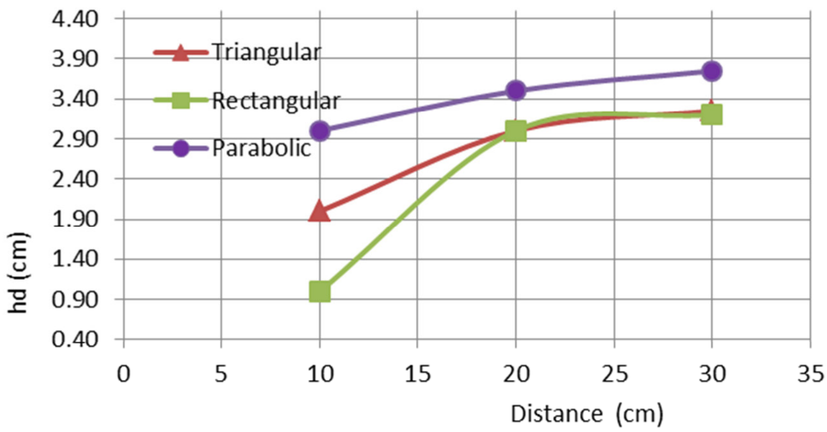

Figure (11) Variation of Downstream Water Profile with Different Shape of Weir (Ag=4.9cm^2, d=2.5cm, hu=2cm)

5. Conclusion

The main conclusions that results from this study and can be considered as major points that must be taken into consideration are listed below:

1-The non-regular shape of gate have significant influence on discharge – area gate relationship regardless the shape of weir.

2- The non-regular shape of gate has important effects on discharge coefficient – area gate relationship regardless the shape of weir.

3- The complex relationship result between Reynolds number and cross sectional area of flow that passes through gate due to effect of over flow velocity and under flow velocity interaction.

4- The vertical distance between weir and gate have major effect on flow rate regardless the shape of weir and gate respectively.

5-The vertical distance between weir and gate have a vital role in the assessment of the value of discharge coefficient.

6- The direct relationship between the flow rate that crosses the combined hydraulic structure and Reynolds number.

7- Complex relationship between discharge coefficient and Reynolds number due to overlapping between over flow velocity and under flow velocity of combined device.

8- Nonlinear water surface profile occurs in downstream of flume.

9-The non-regular shape of gate have major effects on the quantity of discharge that crosses the composite hydraulic structure.

10-The non-regular shape of weir and gate respectively have major influence on depth of water in downstream zone of the flume.

11-The non-regular shape of half ellipse gate plays a significant role in assessing the major parameter that dominates the hydraulic response of composite hydraulic structure.

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